Thoughts on Radiation Shielding for PX Front-End Test Facility

Bob Webber, August 5, 2011

This note contains thoughts and information on radiation shielding that might pertain to considerations of a site for a Project X Front-End Test Facility.

Fermilab Radiation Protection Requirements and Practices

The Fermilab Radiation Control Manual (FRCM) is the Laboratory's ES&H reference document for radiation control.

FRCM (February 2010 Revision) Tables 2-6 and 2-7, shown below, summarize the required controls depending on the levels of radiation expected from normal operation of a facility and from possible accidents. No special precautions are required where radiation levels are expected to be less than 0.05 mrem/hr under normal operating conditions and below 1 mrem total dose per accident. These values should establish the design objectives for new, stand-alone radiation shielding enclosures. Shielding enclosures constructed within spaces already designated as Controlled Areas can allow normal rates and accident doses up to five times higher without a change in the designation of the area. Finally, Controlled Areas with minimal occupancy allow radiation levels up to twenty times higher yet, 5 mrem/hr and 100 mrem/accident.

Table 2-6 Control of Accelerator/Beamline Areas for Prompt Radiation Under Normal Operating Conditions (refer to Article 236.2(b))

Dose Rate (DR) Under Normal Operating Conditions	**Controls**
DR < 0.05 mrem/hr	No precautions needed.
0.05 ≤ DR < 0.25 mrem/hr	Signs (CAUTION -- Controlled Area). No occupancy limits imposed.
0.25 ≤ DR < 5 mrem/hr	Signs (CAUTION -- Controlled Area) and minimal occupancy (occupancy duration of less than 1 hr).
5 ≤ DR < 100 mrem/hr	Signs (CAUTION -- Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
100 ≤ DR < 500 mrem/hr	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
DR≥ 500 mrem/hr	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Table 2-7 Control of Accelerator/Beamline Areas for Prompt Radiation Under Accident Conditions When It is Likely that the Maximum Dose Can Be Delivered (See Article 236.2b for more details)

Maximum Dose (D) Expected in 1 hour	**Controls**
D < 1 mrem	No precautions needed.
1 < D ≤ 10 mrem	Minimal occupancy only (duration of credible occupancy < 1 hr) no posting
1 ≤ D < 5 mrem	Signs (CAUTION -- Controlled Area). No occupancy limits imposed. Radiological Worker Training required.
5 ≤ D < 100 mrem	Signs (CAUTION -- Radiation Area) and minimal occupancy (duration of occupancy of less than1 hr). The Division/Section/Center RSO has the option of imposing additional controls in accordance with Article 231 to ensure personnel entry control is maintained. Radiological Worker Training required.
100 ≤ D < 500 mrem	Signs (DANGER -- High Radiation Area) and rigid barriers (at least 4' high) with locked gates. For beam-on radiation, access restricted to authorized personnel. Radiological Worker Training required.
500 ≤ D < 1000 mrem	Signs (DANGER -- High Radiation Area) and 8 ft. high rigid barriers with interlocked gates or doors and visible flashing lights warning of the hazard. Rigid barriers with no gates or doors are a permitted alternate. No beam-on access permitted. Radiological Worker Training required.
D ≥ 1000 mrem	Prior approval of SRSO required with control measures specified on a case-by-case basis.

Specific Information and Considerations for a 10 MeV Test Facility

Neutron radiation from primary proton or H^- beams dominates shielding concerns for personnel protection. Equations for the radiation (neutron) source term and for neutron transmission through concrete in the low-energy range relevant to a Project X Front-End Test Facility are given as Equation 1 and Equation 4 respectively in the HINS Linac Shielding Assessment document. They are included below:

$$S(E, r, \theta_s) = 2 \times 10^{-5}(1 + E^{0.6})\left(1 - e^{-3.6E^{1.6}}\right)/\left(0.3048\, r\left(\theta_s + 40/\sqrt{E}\right)\right)^2$$

Equation 1: Dose in mrem per proton at a distance r ft from the loss point and at an angle of θ_s degrees with respect to the beam direction. The proton energy E is measured in units of GeV.

$$A(E) = 10^{\frac{-T_{conc}}{3}/(1-0.8\,e^{-5*E})}$$

Equation 2: The amount by which neutron radiation is reduced after passing through T_{conc} feet of concrete. E is the neutron energy in GeV.

The shielding required for a Project X Front-End Test Facility can be estimated using the equations and methodology applied in the HINS Assessment, which has received Fermilab ES&H approval. That methodology uses the following conservative assumptions:

1. The energy of each neutron equals energy of the primary beam
2. The $1/r^2$ reduction in radiation flux from a point loss source applies only from the loss point to the inner surface of a shielding wall; the rate at that surface is then taken as a uniform flux to be attenuated by the shielding.

The HINS assessment also describes the design of a 10 MeV beam absorber with shielding that is shown by MARS simulation to provide a factor of ≥1000 radiation attenuation relative to beam loss on an unshielded target, e.g. a standard beam pipe. This absorber with all steel and polyethylene shielding has been fabricated and is presently located in the Meson Detector Building.

In the following considerations relevant to a Project X Front-End Facility, these assumptions are used:

1. Continuous beam rate of 1 mA at a maximum energy of 10 MeV.
2. All radiation rates are assumed to be at 0 degrees relative to the beam direction. This is the worst case, but the angular sensitivity at these energies is low, i.e. factor-of-two scale.
3. The beam line (beam loss point) is 3 feet from the inner surface of the enclosure shielding wall.

For a useful sense of scale, note that Equation 4 from the HINS assessment gives a factor-of-ten radiation attenuation for 10 MeV neutrons for each 9 inches of concrete shielding.

A uniform six-foot thick concrete shield gives a transmission factor of 4E-9 for 10 MeV neutrons. Applying the radiation source term from Equation 1, one finds that this shielding would limit external dose rates, due to full, continuous beam losses, to 0.035 mrem/hr. This is sufficient to meet the “no precautions needed” criteria for normal operation. In this case, accident conditions need not be considered separately, since continuous full beam loss is assumed.

This simple uniform shield analysis does not consider entrance labyrinths or cabling/utilities penetrations, which will dominate the shielding considerations. Figures 5.6 and 5.8 from TM-1834, “Radiation Physics for Personnel and Environmental Protection” by Don Cossairt, copied below, are the accepted transmission curves for the first and subsequent legs of a labyrinth with multiple right-angle legs. The ES&H group maintains a simple spreadsheet to facilitate labyrinth calculations consistent with TM-1834 curves. It is readily seen from these curves that, to approach the 4E-9 transmission factor afforded by six feet of concrete, a labyrinth with a minimum of four legs is necessary.

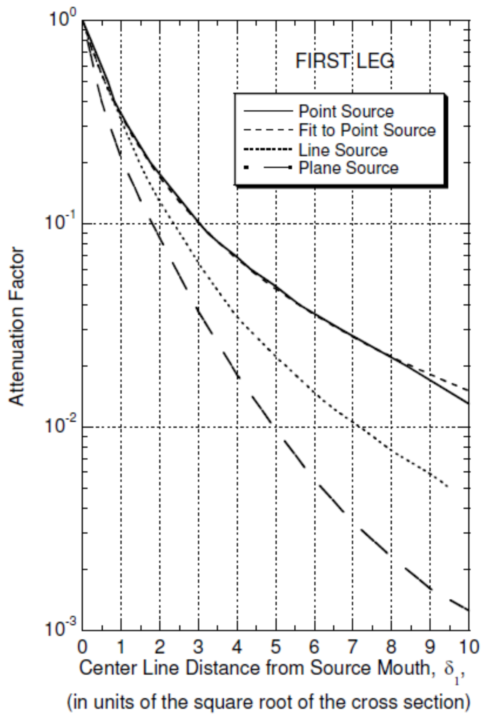

Fig. 5.6 Universal transmission curves for the first leg of a labyrinth as a function of normalized distance δ_1 from the mouth. The fit for the point source curve represented by Eq. (5.4) is also included. The curve for a plane source is also suitable to use with an off-axis point source. [Adapted from (Go75) and (Co95).]

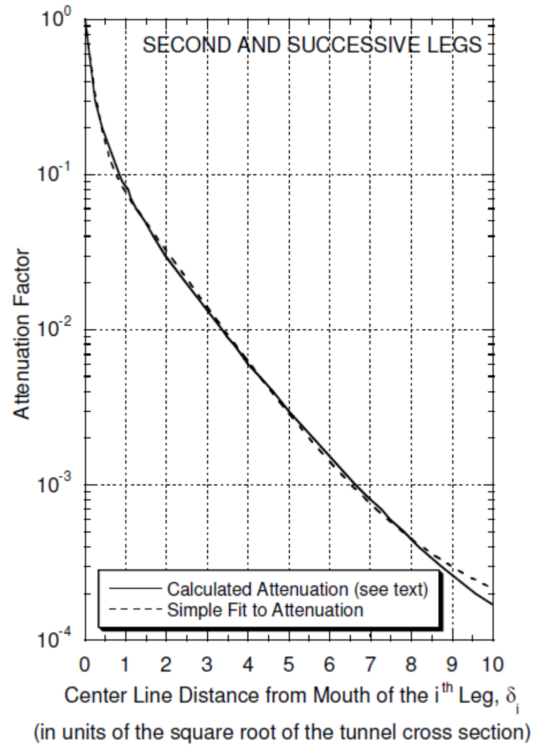

Fig. 5.8 Universal transmission curve for the second and subsequent legs of labyrinths as a function of normalized distance from the center of the previous turn δ_i. The calculated attenuation (solid curve) is that reported by Goebel et al using the code AMC. The dashed curve is the fit provided by Eq. (5.6). [Adapted from (Go75) and (Co95).]

Assuming a labyrinth 6 feet high by 4 feet wide labyrinth (one unit length = sqrt(24) ~5 ft), a four-leg design with Leg 1 being 10 feet and Legs 2, 3, and 4 each 25 feet in length achieves the 4E-9 transmission factor. Some relief (a factor of five at most) is obtained from the geometric factor described in Equation 2 of the HINS Shielding Assessment if the labyrinth entrance is located a distance away from any credible loss point. In any case, the labyrinth and labyrinth walls lay down a foot print of considerable size that must be accommodated at any site not already providing equivalent entrance labyrinths.

Applying the same transmission curves and methodology to an 8" diameter cable duct (one unit length = sqrt(0.35) ~0.6 ft), a three-leg path with Leg 1 having a length of 2 feet and Legs 2 and 3 each a length of 6 feet yields the transmission factor of 4E-9.

For labyrinths and other penetrations, the loss of shielding efficacy due to 'short circuit' paths, as discussed in Section 4.2 of the HINS Shielding Assessment, must be considered and mitigated.

An alternative to the 'build to withstand all possibilities', 'no precautions needed' approach is to maintain the bulk shielding, but to place special controls on the areas in the vicinity of the labyrinth and penetration exits. If these areas are designated as minimal occupancy, Controlled Areas, two orders of magnitude relief is obtained on the attenuation that must be provided by the labyrinths and penetrations.

Another approach, which is typical at Fermilab, is to treat normal conditions and accident conditions separately. Under normal conditions, beam is deposited in a suitably designed absorber within its own shielding ‘box’, relieving the demand for bulk enclosure shielding in proportional to that afforded by the absorber shielding. For the HINS 10 MeV absorber design, this is a factor of 1000! This factor would allow reducing the thickness of the bulk shielding by 2 feet, e.g. from 6 feet to 4 feet, and would make labyrinth design considerably more manageable.

To the extent that the shielding alone may be inadequate to limit doses under accident (beam loss other than in the absorber) conditions, doses are limited by ensuring that the duration of any accident is suitably short. This is justifiable if any accident is inherently limited in duration (e.g. the machine melts down) or if accidents are detected and terminated by approved interlocked radiation detectors. In the HINS case, interlocked detectors with one second response time limit the accidental dose to 1/3600 the hourly dose, a factor comparable to that offered by the absorber shielding under normal conditions. This makes the easing of shielding requirements for normal conditions and for accident conditions roughly the same scale.

As is written in the HINS Linac Shielding Assessment, no issues are anticipated with surface water, ground water, or air activation for a continuous 1 mA, 10 Mev beam.